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# **Space Robotics - Recent Accomplishments and Opportunities for Future Research**

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*The 1991-92 Annual Report  
of the  
Langley Research Center  
Guidance, Navigation, and  
Control  
Technical Committee*

*September 1992*



**- Space Robotics -**  
**Recent Accomplishments and**  
**Opportunities for Future Research**

**Guidance, Navigation, and Control Technical Committee**  
**1991-92 Annual Report**

**Committee Membership:**

Dr. Raymond C. Montgomery, Chairman  
Mr. Carey S. Buttrill  
Mr. John T. Dorsey  
Dr. Jer-Nan Juang  
Mr. Frederick J. Lallman  
Dr. Daniel D. Moerder  
Mr. Michael A. Scott  
Mr. Patrick Troutman  
Dr. Robert L. Williams II

**Introduction**

The Langley Guidance, Navigation, and Control Technical Committee (GNCTC) was one of six technical committees created in 1991 by the Chief Scientist, Dr. Michael F. Card. During the kickoff meeting Dr. Card charged the chairmen to:

- 1) Establish a cross-center committee
- 2) Support at least one workshop in a selected discipline
- 3) Prepare a technical paper on recent accomplishments in the discipline and on opportunities for future research.

The Guidance, Navigation, and Control Committee was formed and selected for focus the discipline of Space Robotics. This report is a summary of the committee's assessment of recent accomplishments and opportunities for future research. The report is organized as follows. First is an overview of the

data sources used by committee. Next is a description of technical needs identified by the committee followed by recent accomplishments. Opportunities for future research ends the main body of the report. It includes the primary recommendation of the committee that NASA establish a national space facility for the development of space automation and robotics, one element of which is a telerobotic research platform *in space*. References 1 and 2 are the proceedings of the two workshops sponsored by the committee during its 6/91 through 5/92 term.

The focus of the committee for the 6/92 - 5/93 term will be to further define to the recommended platform *in space* and to add an additional discipline which includes aircraft related GN & C issues. To the latter end members performing aircraft related research will be added to the committee. (A preliminary assessment of future opportunities in aircraft-related GN&C research has been included as appendix A.)

## Technical Database

This section summarizes the technical database on which this report draws. The database consists of committee-sponsored technical workshops, and on the expertise and experience of the committee's members that participated in the preparation of this report.

### Workshops:

The committee sponsored the following two workshops during the June 1991 through May 1992 term:

1. "1991 NASA Langley Workshop on Automation and Robotics for Space-Based Systems", December 10, 1991.

### Highlights:

Proceedings have been published as NASA CP 10098; 19 technical presentations made, reference 1.

2. "Ongoing Progress in Spacecraft Controls", January 13, 1992. Hereafter referred to as the Mars Mission Workshop.

**Highlights:**

Jointly sponsored with the North Carolina State University Mars Mission Research Center (M<sup>2</sup>RC); 7 technical presentations made, proceedings have been published as NASA CP 10099.

Keynote presentation made by Professor Jerry Walberg: "Review of the Mars Mission Scenarios".

**Expertise and Experience of Participating Committee Members:**

1. Raymond Montgomery (Chairman):  
Past member of AIAA Guidance and Control TC. Current Chairman of Human Interface Working Group of the AIAA Automation and Robotics Committee Standards. This activity provided briefings on robotics from NIST, NASA Goddard, NASA MSFC, United Technologies-USBI, and JPL, which factored into this report as background material. Currently working as a member of the Space Station Assembly, Dynamics, and Control team at LaRC.
2. Carey S. Buttrill  
Served on AIAA Flight Simulation TC. Experience in modeling and simulation of rigid and flexible aircraft. Interests include flutter prediction and suppression, turbulence and actuator modeling, and controls design in a multidisciplinary, conceptual design context - specifically for a supersonic transport class vehicle.
3. John T. Dorsey  
Experience with spacecraft structural concepts and on-orbit spacecraft construction techniques. Areas of interest include: Space Cranes, structural dynamics, passive vibration control, and preshaped command input techniques.

4. **Dr. Jer-Nan Juang**  
Experience with system identification and control of flexible structures. Interests include dynamics and control of flexible spacecraft and manipulators, learning control and neural networks.
5. **Dr. Daniel D. Moerder**  
Experience in optimization and nonlinear optimal control, order reduction techniques, statistical methods, output feedback, integration of remote atmospheric data sensors in guidance systems. SCB Guidance Group Leader, Task Leader for the National Launch System ADP2202 guidance technology development task, Program Manager for the Coherent LAunchsite Wind Sounder (CLAWS) demonstration.
6. **Mr. Michael A. Scott**  
Experience in control law design. Presently working on the space shuttle robotic manipulator control system. Interests include learning systems, adaptive control systems, and robotics and construction techniques
7. **Mr. Patrick Troutman**  
Currently works in the Langley Space Station Office and has recently participated in several Space Station Freedom design studies including the Critical Evaluation Task Force (CETF), the Phased Program Task Force (PPTF), the Manned Mars Accommodation Study, and the Lunar Base Accommodation study. He was the technical lead in conceptualizing and accessing the assembly of Space Station Freedom using pre-integrated structures. Subsequent to Space Station Freedom restructuring he lead a study to access the power system sun-tracking requirements and station controllability for the newly defined configuration flight modes.
8. **Dr. Robert L. Williams II**  
Experience in applied real-time control of distributed telerobotic systems. Primary work in the kinematics, dynamics, and control of manipulators. Additional interests include kinematically redundant manipulator systems, disturbance compensation for space manipulators, design and analysis of robotic mechanisms, computer graphics simulations, symbolic computing, manipulator gravity compensation for micro-g simulation, flexible

manipulators, parallel robotic mechanisms, and variable geometry trusses (VGTs).

## Technical Needs

This section presents current technical needs in space robotics as identified by the committee. First, however, an issue is raised which does not deal with technology but rather communication between the developers and users of robotic technology. A major impediment to space implementation of robotic systems is that the state of the art is often overstated. This results in a gap between existing technology and expectations from potential robotic system users and program funding sources. The capabilities and limitations of the present technology must be understood and emphasized to NASA management. The attempt here is to cite the state of the art as realistically as possible even though it may be quite different from the expectations created by overstatements of capabilities. This section first addresses general technology needs. It then turns to specific needs concerning automated on-orbit positioning and technology for robotic trajectory synthesis.

### A. *General Technology Needs*

The biggest single need in the NASA telerobotics field is a U.S. funded, designed, built, and operated telerobot development platform facility in space. This system should be built relatively simply and cheaply (compared to the ill-fated Flight Telerobotic Servicer (FTS) program), on a small scale which can grow in the future. Space Station Freedom should be the targeted mission, and future missions can be supported with initial successes in this program. The U.S. should not rely on Canadian technology (e.g. RMS, SPDM) considering the reluctance of foreign governments to share technical information with competitors in the telerobotic field. With our own development system in space, NASA gives a focus to telerobotics research effort as well as a base-line configuration for future improvements. Further, on a purely technical basis, the first flight of the Space Shuttle Endeavour vividly demonstrated that ground testing cannot always predict problems that may occur in space. Specifically, attempts at operations required to rescue the stranded Intelsat communications satellite were successful in water tank testing but not in space. Real experience

needs to be established in critical areas such as automated assembly techniques so that we are not surprised by problems similar to those encountered in the Endeavor rescue mission. A space platform facility would enable automation and robotics research in a space environment thus eliminating these surprises.

General technical needs of research in the robotics area were identified by workshops sponsored by the committee. The workshops outputs are summarized below:

The 1991 NASA Langley Workshop on Automation and Robotics for Space-Based Systems demonstrated the depth of interest in automation and robotics at NASA Langley. While the technology discussed is applicable to general space missions, the focus of this workshop was in support of near-term NASA missions, such as Space Station Freedom. The nineteen presentations included current, ongoing projects which are gearing up to support EVA and IVA telerobotics for Space Station Freedom, hand controllers and force control modes for teleoperation, vision and other sensor feedback, neural networks for robotic control, automated assembly of truss structures, active vibration suppression for the SRMS, space crane concepts, modeling, simulation, and control of flexible manipulators, and passive dynamic controllers for robots.

The Mars Mission workshop focused on controls development for the Mars Mission. For NASA, this mission looms in the far future and possesses very advanced technology which will tend to drive research plans. The opening paper by Prof. Jerry Walberg dealt with possible ways of reducing the time required to perform a Mars mission because of physiological constraints imposed by having a human crew. Some mission concepts require lunar bases as a stepping stone to the Mars mission. Because of the large size of the vehicles required, almost all of the mission scenarios require the technology to assemble Mars Transfer Vehicles in Low Earth orbit. Because of the limited amount of human resources which will be available on orbit for EVA and IVA operations, efficient on-orbit construction techniques and an optimum mix of human and robotic operations will be required to provide enabling technology for the Mars mission.

Relative to the Mars mission, major problems must be overcome, and the state of the art relative to the need is, indeed, depressing. The NASA/RPI Center



for Intelligent Robotics Systems for Space Exploration (CIRSSE) recently held its annual review. Reference 3 is the proceedings of the review. Technological deficiencies lie mainly in the area of sensing systems and vision systems operating in an unknown environment, task allocation and planning, and in the area of precision telerobotic control of large, flexible robot systems.

Another problem identified during the Mars Mission workshop, is that of time-delay. Time-delay caused by remote operation dictates that equipment have the capability of automatic operation consistent with the delays involved in remote monitoring and directing the process. This is, of course, true for any operation. The Mars Mission stretches technology, however, in that delays on the order of a half-hour or more are anticipated necessitating a level of automation not generally required or available in current telerobotic equipment.

*B. New concepts for automated on-orbit payload positioning*

Currently, many of the requirements needed to design an on-orbit assembly device have not been defined. For example, the total size and mass of the lunar and Mars spacecraft, as well as the sizes and masses of the spacecraft components transported to orbit vary widely with the concept being proposed. Important parameters such as the mass and volume capabilities of the launch vehicles, and the infrastructure available on orbit to perform assembly operations will not be known for many years. Consequently, wide ranges in launch vehicle capability, spacecraft mass and size, and infrastructure options must be assumed. Thus, a viable assembly device must be very adaptable and capable of being modified in response to changes in requirements as they become better defined.

Some of the devices which have been suggested as being on-orbit payload positioning devices are: the Remote Manipulator System (RMS), Space Station RMS (SSRMS), Special Purpose Dextrous Manipulator (SPDM), and the Flight Telerobotic Servicer (which has been canceled). All of these devices suffer from structural deficiencies, such as flexibility, lack of strength, and nonlinear response to applied forces. These limitations generally occur because the joints are very flexible and have nonlinear structural behavior by nature of their design: all of the load paths through the joints involve mechanisms (such as gears

and shafts) and motors. More importantly, these concepts lack the adaptability and versatility needs as stated previously: that is, they have fixed reach and dexterity capabilities which are very difficult or impossible to change without redesigning the device.

### *C. Technology for Robotic Trajectory Synthesis*

Space robotic systems will have to operate autonomously and efficiently, either singly or in multiple robot combinations. The requirement of autonomy dictates that the characteristics and limitations of their onboard sensor suites are explicitly accounted for in the robots' onboard motion planning. These motions, additionally, must be planned in such a manner that loss or degradation of sensors and/or physical motion capability will not result in catastrophic failure to complete the task - The robotic system must degrade gracefully. The requirement for autonomous robots to operate in cooperation implies a requirement for efficient techniques for solving task planning trajectory synthesis problems as cooperative games. A particular concern in the latter area are tradeoffs associated with the degree of distribution or centralization of command synthesis and sharing of sensor data. Another concern is the issue of singular optimal solutions to cooperative multirobot task planning problems stemming from redundant capability.

## **Recent Accomplishments**

A significant recent accomplishment related to delay was the telerobotic assembly task demonstrated by JPL. In that task an operator at the remote site of JPL in California successfully navigated a robot arm into a complex large structural assembly (a PAM-D frame) at the Kennedy Space Center, 3000 miles away. A gross motion planner was used to accomplish this task. Although the time-delay present in that operation (2 seconds) is substantially less than that expected during the Mars mission the task represents an achievement at the leading edge of the current state of the art.

Several recent accomplishments have been demonstrated at NASA Langley that improve the capability for telerobotic operations. A powerful naturally-

transitioning rate/force controller (NTRFC) for teleoperation of manipulators has been recently developed and demonstrated, reference 4. The algorithm is a rate controller (based on inverse-Jacobian control) with a force accommodation, or active force compliance running locally on the manipulator. When the manipulator is in free motion, it is a rate controller. When contact is made with the environment, force feedback causes a natural transition from rate to force control. Natural transition indicates that no software switch is required. The NTRFC can be used with or without force reflection to the human operator. The astronauts prefer rate control in free-motion and position control in contact. The NTRFC provides a control method very similar to this.

A hand controller evaluation study was recently completed at NASA Langley, reference 5, in which subjects compared different hand controllers and force control conditions in teleoperation of a manipulator to complete representative space tasks. The subjects had no prior experience with telerobotics. No significant differences were found for task completion times, which was the primary metric in the study. However, secondary results indicate that force-reflection may reduce the forces exerted against the environment. Further study is required because the subjects were not asked to minimize interaction forces. Minimum force, not time, is a more critical metric for space tasks, because avoidance of breakdowns is more critical than fast performance.

A machine vision task is underway at NASA Langley for inspection of TPS shuttle tiles at KSC. A prime component of this technology recently demonstrated is anomaly detection in field conditions. While this technology is demonstrated on earth, it has potential of space applications.

A LASER proximity sensor has been demonstrated at NASA Langley for automated robotic control. A coherent LASER RADAR system is used for detecting and avoiding collisions of a manipulator with its environment. The sensor(s) may be placed at the robot end-effector or anywhere along the length of the arm for collision avoidance. In an alternative technology for implementing collision avoidance, NASA Goddard recently demonstrated a capaciflectance system.

Continued progress has been demonstrated at NASA Langley in the automated assembly of space-based truss structures. This effort is exploring automated robotic operations, with only a supervisory role for the human operator. Recent accomplishments in this area have been automated error tracking/reversal, implementation of an end-effector microprocessor for local control functions, and the addition of panels to the truss assembly sequence.

On-going work in the area of dynamic control of space manipulators is progressing well at M.I.T., supported by NASA Langley. The identification of dynamic singularities, reference 6 is crucial to the effective operation of space manipulators with non-stationary bases, moving either freely or on an elastic base. The extension of control algorithms for the dynamic control of fixed-base manipulators on earth to space manipulators with moving bases is possible using the concept of the virtual manipulator, reference 7. An experimental system with a servoed, six degree-of-freedom, hydraulic platform is under development to test on earth control algorithms for the micro-gravity dynamics of space manipulators.

### **Opportunities for Future Research**

The base-line component technologies of telerobotics are well developed (i.e. manipulator arms, sensors, communications, computing, machine vision in a controlled environment, control algorithms, dynamics modeling). There are three major areas for further work in telerobotics. 1) Continue to improve the component technologies of telerobotics. 2) Refine the systems approach to telerobotics. Given the component technologies, make all perform and interact efficiently to derive an overall system with high reliability and performance. 3) Apply the existing technology in space, or in high-fidelity earth simulations of space. The goal of all three areas should be to produce a new generation of intelligent space telerobots with increasing autonomy, better performance, more robust and safe systems, and increased user confidence. In order to succeed, NASA must have real telerobotic systems operating in space. Application of actual space telerobotic systems is far lagging the capabilities demonstrated in laboratories on earth.

## *A. Space manipulator dynamics*

Continuation of the theoretical modeling, simulation, and experimental verification of manipulator system dynamics in micro-gravity is required for the next generation of space telerobotics technology. In particular, disturbance compensation is important in order to minimize the base reaction forces and moments from the manipulator to its base. In a micro-gravity environment, these shaking forces must be small in order to maintain safety, perform experiments, and the reliability of the entire space system. The effect of dynamic singularities [4] on the performance of space-based manipulator systems must be understood and controlled.

One of the major problems facing space telerobotics today is an accurate earth-based hardware simulation of the dynamics of a space-based manipulator system. The development of such hardware simulations would increase the potential applications, interest, and faith in telerobotic systems while reducing the development cost. It is very difficult and expensive to reproduce the dynamics of a space manipulator with look-alike hardware on earth. It is more feasible and versatile to simulate space dynamics with a reduced hardware system on earth (e.g. using a Stewart's platform to model any moving or elastic platform base for a space manipulator); however, this reduces the believability of results and conclusions obtained from the simulation. This dilemma would be alleviated by obtaining actual dynamics data from a real manipulator system in space and validating the earth-bound hardware simulation with it.

## *B. Kinematically redundant manipulator research*

A continuation in redundant manipulator research is necessary to ensure better performance in future telerobotic systems. A kinematically redundant manipulator is one which has more freedoms than necessary to accomplish a general task. For example, a general spatial task requires six degrees of freedom (three translations and three orientations); any manipulator with seven or more axes is therefore a redundant manipulator in this space. The extra freedoms can be used to optimize performance of the manipulator, in terms of avoiding singularities, avoiding joint limits, avoiding obstacles, minimizing base reaction

forces, maximizing mechanical advantage, minimizing required joint rates or total energy, achieving active vibration suppression, and providing failure back-up operation, to name some examples. The major need in manipulator redundancy research is applied redundancy resolution; the theory is well developed but the real applications are lagging. There are at least four categories of manipulator redundancy. 1) A manipulator arm with more joints than task freedoms. 2) Multiple arm coordination with one task. 3) Manipulator arms carried by a mobile transporter such as a track or a free-flying vehicle. 4) Compound manipulators, e.g. Space Crane (or SSRMS) with manipulators mounted on the end, or the original concept of the Canadian Special Purpose Dexterous Manipulator (SPDM), a five degree-of-freedom trunk plus two seven degree-of-freedom arms (reference 2, page 28). For any of these classes of redundancy, the concept of transparent operator control needs to be developed and applied. That is, the operator (or automated system) should not be concerned with each joint of these highly redundant manipulator systems, but only with the motion of a coordinate frame attached to the end-effector.

### *C. Communication time delays*

With a drive to reduce the budget while maintaining NASA performance, smaller, more autonomous missions have been called for. An important research topic is the communication time delay from earth-based controllers to autonomous space-based telerobotic systems, and back again. The Viking project resolved this by going to full automation with events activated by telemetry. One approach to solving this problem is to use analytic prediction based on models of the process at the robotic end of the process. Defining the limits of prediction systems at the command end for both monitoring and interaction can be a fruitful area of research. This problem has been addressed to a limited extent in the JPL/KSC demonstration in the framework of teleoperation. However, the limits of operation as dependent on time delay have not been defined. NASA Langley has an opportunity to study time delays in both telerobotic and in autonomous robotic systems.

#### *D. New concepts for on-orbit payload positioning devices*

LaRC should pursue the development of a new space crane concept which is specifically designed for assembling large space systems on orbit, and which is adaptable, versatile, and robust. The space crane would feature erectable truss booms (for high strength and stiffness) which are connected by articulated truss joints. The articulated truss joint for the space crane achieves high strength and stiffness by operating at the structural level, using kinematically stable truss structure and linear actuators to induce joint rotation. Adaptability is inherent in the erectable truss structure: the truss bay size (and thus the stiffness) can easily be changed by changing the strut lengths, and the structural strength can be changed by increasing the strut modulus or area. Both of these changes can be made without changing the joint hardware. Truss bays can quickly be added to the booms to increase crane reach, or booms and articulating joints can be added or deleted as needed to change the work envelope, leading to a very versatile concept.

The concept of variable geometry trusses is similar to the space crane discussed above. VGTs share the good stiffness, strength, modularity, and versatility mentioned for the space crane. Applications include payload positioning for space assembly, and serving as the carrier vehicle to transport smaller manipulator arms to a worksite. VGTs are structurally more complex than space cranes; the cost is that more complex control is required, but the benefit is enhanced dexterity.

#### *E. Passive vibration control of large space trusses and space cranes.*

Currently a great deal of emphasis is placed on research in the area of active vibration control of large space structures. However, passive damping offers a much simpler, less costly, and more robust alternative for many applications. An excellent area of opportunity for LaRC is investigating techniques such as viscous damping and preshaped command input for devices such as the space crane. Passive damping could be especially beneficial for space cranes because the space crane modes and frequencies are constantly changing; as different payload masses are added, and as the crane configuration changes during positioning operations. The preshaped command input technique operates

on the principle of modifying the system input so as not to excite responses in frequencies of interest. Advantages of the preshaped input technique include: achieves excellent performance, is simple to implement, can be applied simultaneously to multiple modes, is robust to errors in system frequencies and damping ratios, and requires no sensors or feedback.

*F. Optimum division of human and automation tasks for assembling space systems on orbit*

Currently, a great deal of work is being done separately in the areas of manned (Spacecraft Structures Branch) and robotic (Automated Structural Assembly Laboratory) assembly for in-space assembly and construction. At this stage, each activity is focusing on defining and developing those capabilities to which it is best suited, but each activity should also be recognized as having some deficiencies in certain applications. An area of opportunity for research exists in determining what the best mix of manned and automated tasks are for assembling large space systems on orbit. Particular emphasis should be placed on using the best features of both human and automated assembly so that the two complement each other.

*G. Trajectory & task planning technology for autonomous telerobotic systems*

This opportunity area includes, primarily, enhancements to the state of the art in nonlinear control optimization theory to handle the special needs of autonomous space telerobots. Opportunities include robust/reconfigurable trajectory optimization, optimal trajectory planning subject to constraints dictated by space telerobotic sensor suites, applications of cooperative game theory and hierarchical model decomposition techniques to multirobotic task planning.

*H. Enabling the robot to learn using advanced identification methods*

This subject, more commonly called adaptive control, is a subset of what is typically considered to be artificial intelligence. Artificial intelligence also deals with decision making and task planning. Unfortunately, the technology requisite to incorporate all past information about flexible robot mistakes to improve on the task performance is not yet available. A signal processing algorithm can be



used to replace kinematic inversion of plant dynamics and also allow a natural ability to handle flexibility of robot segments and payloads. Tracking control laws which incorporate linear and nonlinear information measured from past performance will provide added benefit to both terrestrial and space robots.

### *I. Reducing unwanted vibrations associated with robotic maneuvers or construction tasks*

A natural, and efficient method of reducing the vibration associated with a robotic maneuver or a construction task is through the actuators which are already present on the device and strain energy type sensors. One simple approach which offers potential for future payoffs is the use of compliant joints which have the ability sense the strain energy. For example, piezo electric actuators can absorb energy from a structure regardless of how much the structure is nonlinear varying. They offer great potential to flexible manipulators which are built up of truss elements, and they are most efficiently used when they are in a load path where a lot of strain energy exist. In the same manner, the inherent nature of a robotic device is that some joints are always in the load path and can absorb energy passing through the joint. Knowledge of this local strain energy combined with a collocated actuator offers a natural method of absorbing energy. Further, this method of reducing unwanted vibration requires no additional hardware to what already exists on the manipulator. The only requirement are that: (1) The joints are back drive capable and the encoder or tachometer have a sufficiently high resolution of measurement, or a strain or strain rate sensor is present very near the joint and (2) The ability to use that measurement to command a force to the collocated existing joint motor. The violation of the first requirement is the reason why this approach is not used on the Space Shuttle RMS to damp unwanted vibration. This strain energy sensing strategy combined with feedback to existing joint motors naturally handles kinematic nonlinearities *always* present in robotic devices. It has no elaborate control elements, so it may not be a challenging problem; however it is a natural solution which deserves development and experiment.

## *Summary*

In general, the next generation of space telerobotic technology needs to move towards more autonomy, better performance, increased reliability, local control independent of humans, and overall system robustness. System safety and autonomous error condition recovery are needed to support this. The first step is for the U.S. to get back into the space telerobotics field.

***Primary Committee Recommendation:*** The committee's primary recommendation is that NASA develop telerobotic research platform *in space*.

The current thinking of the committee is that this facility should be unmanned and launched on a vehicle other than the space shuttle. This telerobotic system should be controlled from the ground, with a varying mix of teleoperation and autonomous local control with a supervisor on the ground. Representative space mission tasks could be designed into this platform. Time delays, disturbance minimization, active vibration suppression, manipulator dynamics and control in a zero-gravity environment, and optimum use of kinematic redundancy for space manipulators could be studied in the real space environment. The project could be performed with relatively low cost, and the potential payoff in research results and visibility for NASA and NASA Langley telerobotics would be enormous. This research platform could lead naturally to alternate telerobotic systems. Upon initial successes, the applications could be expanded to Space Station Freedom; capture, maintenance, and repair of satellites; space science and experiments; space manufacturing; and space assembly and construction. One of the committees prime goals for the 6/92 - 5/93 term will be to add meat to this proposal by defining technical requirements for the platform and by generating a candidate design.

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## **Appendix A.**

### **Opportunities in Aircraft GN &C Research**

The following is the opinion of GNC-TC member Carey Buttrill and reflect his efforts at canvassing members the Aircraft Guidance and Controls Branch. Opportunities for research in aircraft GN&C are seen as follows:

- (1) Provide a methodology whereby dynamic and control (D&C) issues can be better addressed in the conceptual and early preliminary design phases of aircraft. This will allow D&C issues to impact configuration assessment.
- (2) Achieve integrated control that combines propulsion and inner-loop flight control. The engine manufacturers seek to deliver a complete subsystem that can be specified and verified on the test stand. Engine control involves (among other things) a trade-off between providing performance and stall margin. Opportunities exist to relieve stall margin constraints when flying in benign conditions.
- (3) In the area of HSCT applications, the opportunity exists to apply modern uncertainty design and analysis techniques to a statically unstable HSCT configuration wherein active (phase) stabilization of elastic modes is required. Douglas is interested in looking a new control law modes (flight path control) for landing HSCT and next generation transports. Boeing is also interested in exploring back-side operations to conform to existing shallow approach paths and lower landing speeds for HSCT-class vehicles.
- (4) In the area of navigation, interesting opportunities have arisen thanks to GPS, e.g. autoland capabilities for small aircraft; non-precision approach to closest "land-able surface". Also, autonomous RPV (perhaps a Mars gliding lander?) thanks to microprocessors may be an active area in a few years.
- (5) In the flying qualities area, AGCB has been approached by CALSPAN, who have received requests from manufacturers, about additional side stick controller specifications and design guides.

- (6) Exploit parallel and distributed computing technology to enable larger numerical problems to be solved in reasonable times. For example, computing structured singular values for real parameter uncertainties and for realistic (complex) systems, routinely performing stochastic robustness analysis in a timely manner for realistic (complex) systems, simultaneous simulation/optimization of multiple independent subsystems such as airframe, engine, hydraulic actuators, fuel management, etc.
- (7) Couple current methods of control design with computer graphics and imaging tools to provide alternate perspectives on the controls problem. Interactive computer graphics can be used to modify design and analysis parameters to refine a design or analysis consistent with observed results and trends. Assess impact of virtual reality graphics techniques on optimization and design problems.
- (8) Nonlinear analysis and design methods should be developed to address a fundamental limitation of the majority of the current generation controls methods - linearity. A large portion of the control design effort is in validating a control system designed with a linear model on a more accurate non-linear model of the physical system. Direct non-linear control design or methods to enhance the ability to consider non-linear effects on system performance are required.
- (9) In order for adaptive and self-tuning control methods to become accepted as a feasible technology, methods to validate performance and robustness of these types of systems is required.
- (10) Modeling is an area inextricably connected with controls research. A large portion of the effort of designing control systems goes into the problem of modeling the physical system, understanding the key phenomena which determine the behavior of the system, and identifying physical means by which control of the behavior can be realized. Unfortunately, insufficient emphasis is placed on this aspect of the control problem both from a research perspective and from the technology development / program planning perspective. Many of the delays in technology development programs and many shortcoming and even failures of control systems to

meet design objectives can be traced to improper modeling or a lack of understanding of the physics of the physical system. More coordinated effort should be placed in modeling systems for controls applications.

- (11) An area of active research for almost 10 years has been that of restructurable controls. In its most advanced form, a restructurable control system would be capable of reacting to sudden changes to the aircraft operating condition and/or dynamics by conducting on-line plant identification and control redesign. Applications include battle damage, structural failure, and engine loss. This technology could provide the extra safety margin that enables static instability and its attendant fuel efficiencies as a practical design option for commercial transports (e.g. HSCT)

Finally, table A-1 lists possible areas of aircraft application for various emerging research topics in dynamics and control.

**Table A-1. Aircraft application for emerging D&C research**

<b>Research Area</b>	<b>Area of application</b>
Nonlinear Analysis Catastrophes Chaos Fractals	Maneuver Envelope Expansion
Neural Network Control -type of nonlinear control	Maneuver Envelope Expansion One controller for entire flight regime Parallel implementation Multi-input/multi-output Tolerant to controller damage
Fuzzy Logic Control and/or Expert Systems	Engine Mode Management Efficiency Smooth transitions
Adaptive Control	Near-optimal -for duration of flight -throughout lifespan of aircraft -in presence of icing -in presence of cargo/fuel shift
Restructurable Controls	Passenger Safety Enhancement Battle Damage Tolerance

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13. ABSTRACT (Maximum 200 words)     The Langley Guidance, Navigation, and Control Technical Committee (GNCTC) was one of six technical committees created in 1991 by the Chief Scientist, Dr. Michael F. Card. During the kickoff meeting Dr. Card charged the chairmen to: 1) Establish a cross-Center committee; 2) Support at least one workshop in a selected discipline; and 3) Prepare a technical paper on recent accomplishments in the discipline and on opportunities for future research.  The Guidance, Navigation, and Control Committee was formed and selected for focus on the discipline of Space Robotics. This report is a summary of the committee's assessment of recent accomplishments and opportunities for future research. The report is organized as follows. First is an overview of the data sources used by the committee. Next is a description of technical needs identified by the committee followed by recent accomplishments. Opportunities for future research ends the main body of the report. It includes the primary recommendation of the committee that NASA establish a national space facility for the development of space automation and robotics, one element of which is a telerobotic research platform in space. References 1 and 2 are the proceedings of two workshops sponsored by the committee during its June 1991, through May 1992 term.  The focus of the committee for the June 1992 - May 1993 term will be to further define to the recommended platform in space and to add an additional discipline which includes aircraft related GN&C issues. To the latter end members performing aircraft related research will be added to the committee. (A preliminary assessment of future opportunities in aircraft-related GN&C research has been included as appendix A.)				
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